Report for Project 114045

“Optical slow-wave metamaterials and their tunability/applications”

Research goals

To study optical slow-wave metamaterial structures and explore their tunability and applications, including local enhancement and light absorbers, different types of EIT/Fano resonance, and zero-index artificial metamaterials.

Summary and significance of our research results carried out in this project

1. Classical analog of electromagnetically induced transparency for slow light

A classical effect of electromagnetically induced transparency (EIT) is demonstrated in a planar metamaterials in the ultraviolet regime. The EIT unit cell consists of a vertical cut wire as the bright resonator and two horizontal cut wire pairs as the dark element. The destructive interference between the two resonance paths leads to an EIT-like transmission spectrum of the metamaterial. This metamaterial design that enables excitation and tuning of the classical EIT effect would eventually lead to the development of electromagnetic slow light devices. And this planar EIT structure can be easily fabricated and integrated as ultra-compact sensor with high sensitivity.

In our previous report, some preliminary EIT effort in a dielectric slab waveguide with two nano-sized elliptical silver particles placed inside was proposed. Based on this concept, in this project **we have enhanced the contrast between the transmission peak and dip** by incorporating the Fabry-Perot resonance effect (see Fig. 3 below).

2. Slow light ultra-broadband absorber

We have first designed a slow-wave ultra-broadband thin-film infrared absorber consisting of sawtoothed anisotropic metamaterials with continuous metal film in bottom layer to suppress the transmission. Our design is scalable and can be applied at other frequencies as well.

The absorber we studied in our previous 1-year grant is for microwave. In the present 1-year project, we have demonstrated an infrared broadband absorber based on an array of nanostrip antennas of several different sizes. The broadband property is due to the collective effect of magnetic responses excited by these nano-antennas at distinct wavelengths. By manipulating the

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14. ABSTRACT **A classical effect of electromagnetically induced transparency (EIT) is demonstrated in a planar metamaterials in the ultraviolet regime. The EIT unit cell consists of a vertical cut wire as the bright resonator and two horizontal cut wire pairs as the dark element. The destructive interference between the two resonance paths leads to an EIT-like transmission spectrum of the metamaterial. This metamaterial design that enables excitation and tuning of the classical EIT effect would eventually lead to the development of electromagnetic slow light devices. And this planar EIT structure can be easily fabricated and integrated as ultra-compact sensor with high sensitivity.**			
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differences of the nanostrip widths, the measured spectra clearly validate our design for the purpose of broadening the absorption band. The frequency absorption band with higher than 95% absorbing efficiency has a FWHM of 86% at normal incidence (see Fig. 5 below), and **this is the largest bandwidth for efficient absorption of light that we can find in literature.** The work is published last month in Nano Letters (with an impact factor over 12).

In this project we have also proposed a plasmonic super absorber. This structure is etched on a gold film (see the experimental results of Fig. 8 below; the work will be submitted soon). Our preliminary results have shown that this super absorber can give broadband and polarization-independent resonant light absorption over the entire visible spectrum with an averaged absorption over 90%. This optical absorber can find its application in the field of e.g. photovoltaic devices.

3. Arbitrarily thin absorber with zero-index metamaterial

We have demonstrated that an **arbitrarily thin** metamaterial layer can perfectly absorb or giantly amplify an incident plane wave at a critical angle when the real parts of the permittivity and permeability of the metamaterial are zero while the absolute imaginary parts can be arbitrarily small. This is quite different from a conventional absorber, where the thickness needs to be of wavelength order. This finding establishes a new concept of ultra-thin absorber design and application of zero-index metamaterials.

4. Optically implemented THz metamaterial modulator

Metamaterial absorbers can perfectly absorb an incident wave in a narrow frequency band. In this project, metamaterial absorbers are used to construct terahertz modulators by incorporating amorphous silicon (see Fig. 12 below). This metamaterial device can be used as a **high-speed all-optical** modulator in terahertz regime. Our design is compatible with current semiconductor technologies and can be implemented for other light spectra.

Research results in details

1. We have observed the ultra-compact electromagnetically induced transparency (EIT) phenomenon by the interference between different excitation pathways of the dark mode in a planar metamaterials in the ultraviolet regime. The EIT unit cell consists of a vertical cut wire as

the bright resonator and two horizontal cut wire pairs as the dark element. This EIT system can be considered as a 4-level Y-configuration system, shown in Fig. 1. The atomic medium is transparent to the probe field if the constructive quantum interference between the |3>--|2> and |3>--|2'> transitions emerges.

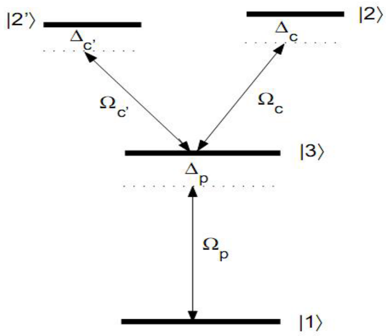

FIG. 1. Y-configuration system

The dark mode resonance is excited by both the electric and magnetic fields when the cut wire pair translates along the wire. The electric and magnetic pathways of exciting the dark mode allows for a giant amplitude modulation of the EIT resonance. Fig. 2 shows the configuration for achieving EIT. This planar structure can also be easily realized in experiment.

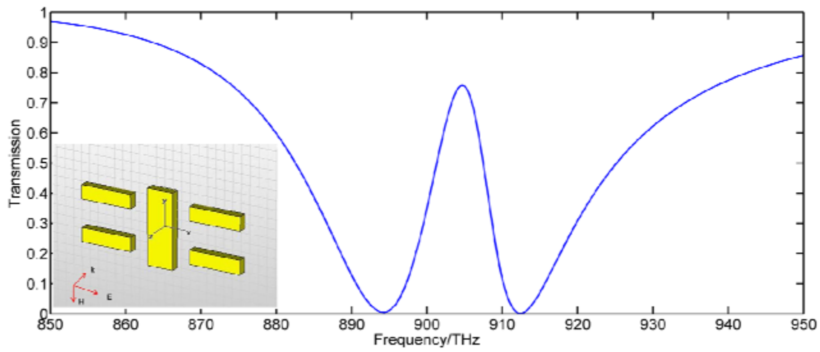

FIG. 2. Schematic diagram of the EIT metamaterial structure

In the previous grant, we have achieved an EIT-like phenomenon inside a single-mode dielectric slab waveguide in which the resonant elements (silver nanoparticles) are placed inside the core layer. However, the contrast between the transmission peak and dip is low, which limits its application. In the present 1-year project, we utilized the idea of Fabry-Perot (FP) resonance to further increase the transmission peak/dip ratio. As shown in Fig. 3, the contrast between the transmission peak and dip can be further enhanced by incorporating the Fabry-Perot resonance effect between two cells formed by one dark particle and two bright particles.

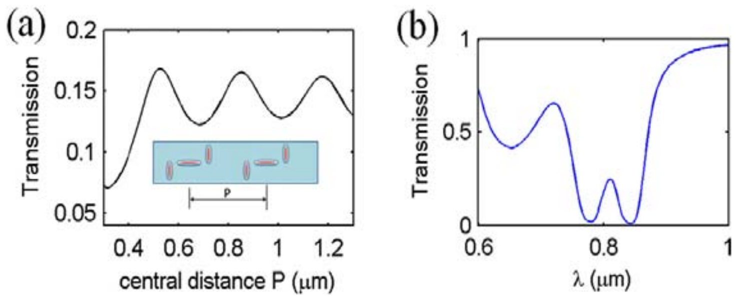

FIG. 3. (a) Transmission variation at wavelength 0.8 um as central distance P between two cells changes. (b) Transmission spectrum corresponding to P = 0.53 um, where the first maximum transmission peak appears in (a).

2. In our designed infrared absorber, which consists of alternating layers of flat metal and dielectric plates, the anisotropic MM (AMM) sawteeth not only independently work as a group of ultra-short vertical waveguides that support slow-light modes at different frequencies so that the incident light at different wavelengths are trapped at positions of different tooth widths, but also help the anti-reflection property due to the gradual change of the effective indices. Fig. 4 shows the diagram of our designed structure.

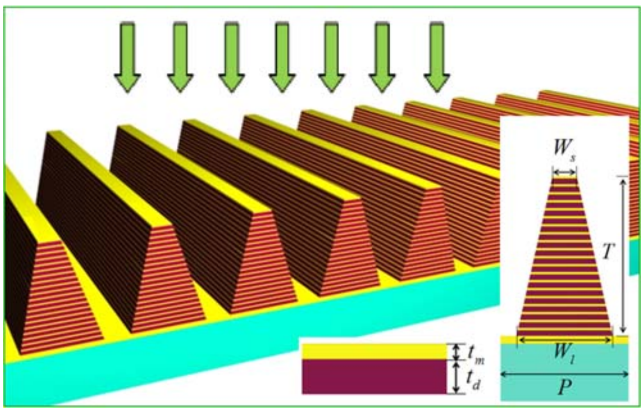

FIG. 4. Diagram of the sawtooth anisotropic metamaterial thin film absorber. P = 800 nm, T = 1000 nm, Ws = 150 nm, Wl = 600 nm, td =35 nm, and tm = 15 nm. Light of TM polarization is incident along +z direction.

The frequency absorption band with higher than 95% absorbing efficiency has a FWHM of 86% at normal incidence. Our absorber also performs very well in a wide angular range, when the incident angle ϕ is smaller than 60°, the structure keeps the performance of very high and ultra-broadband absorption, resembling that at normal incidence, as shown in Fig. 5. Our study can be applied in the field of designing photovoltaic devices and thermal emitters.

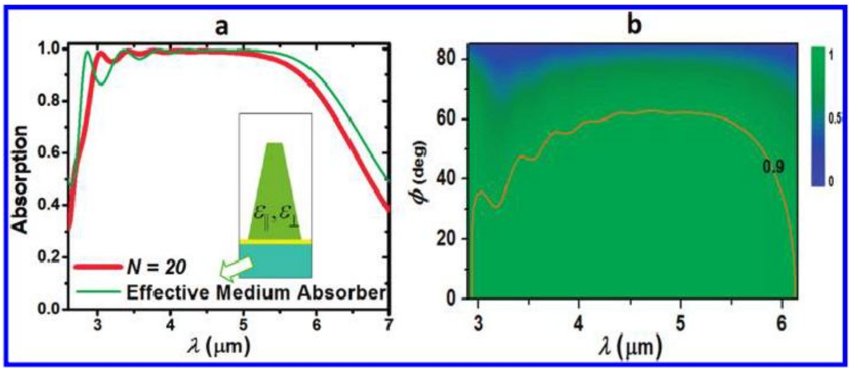

FIG. 5. (a) Absorption spectra for the sawtooth AMM infrared absorber with number of periods N = 20 (thick line) and the effective homogeneous sawtooth structure that is shown in the inset (thin line). (b) Angular absorption spectrum of the sawtooth AMM film.

We have demonstrated another infrared broadband absorber based on an array of nanostrip antennas of several different sizes (see Fig. 6). The broadband property is due to the collective effect of magnetic responses excited by these nano-antennas at distinct wavelengths. By manipulating the differences of the nanostrip widths, the measured spectra clearly validate our design for the purpose of broadening the absorption band (see Fig. 7).

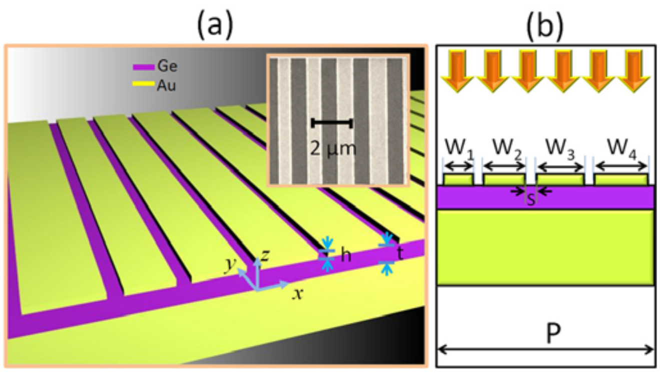

FIG. 6. (a) and (b) Schematic diagram of the proposed three-layered light harvesting absorber. The inset of (a) shows the SEM image of the fabricated sample with P=6.06 um, t=340 nm, and h=16.5 nm. Strip widths

(from W1 to W4) form an arithmetic sequence, with W3=830 nm, the difference D=85 nm, and the separation S=727.5 nm.

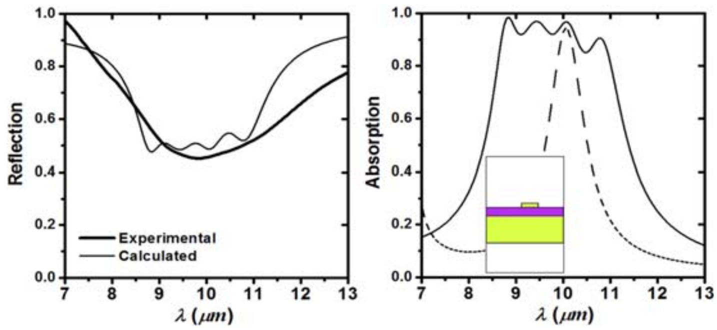

FIG. 7. (a) The experimental (thick curve) and simulated (thin curve) reflection spectra. (b) Comparison of the calculated absorption spectra between the multi-sized antenna (solid curve) and the single-sized antenna absorbers (dashed curve, with the profile shown in the inset).

Besides the infrared absorbers, we have also proposed an optical plasmonic super absorber etched on a gold film. Our super absorber gives broadband and polarization-independent resonant light absorption over the entire visible spectrum (300-750 nm) with an simulated absorption (averaged) above 90%. Fig. 8 shows the SEM image of the fabricated structure and the simulated absorption spectrum.

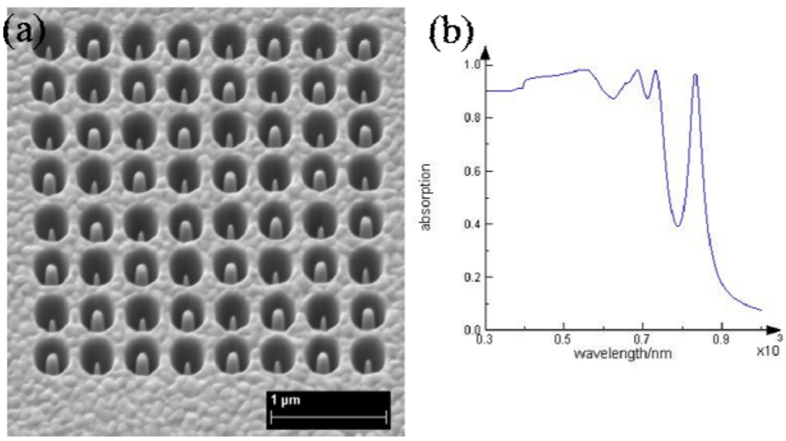

FIG. 8. (a) SEM image of the fabricated structure and (b) the simulated absorption spectrum.

We have also fabricated Au bowtie nanoantenna arrays on silicon substrate for highly efficient optical trapping (see Fig. 9). The manuscript with physical mechanism is in preparation.

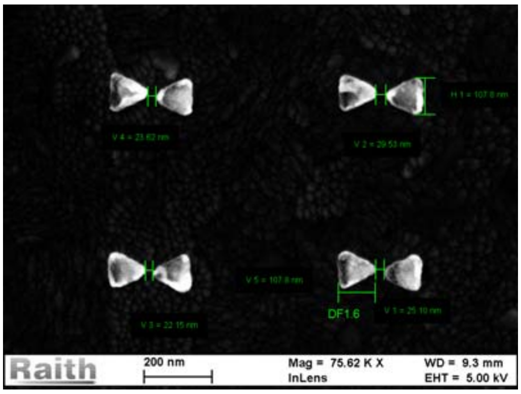

FIG. 9. SEM image of Au bowtie nanoantenna arrays on silicon substrate.

3. We have demonstrated that an arbitrarily thin metamaterial layer can perfectly absorb or giantly amplify an incident plane wave at a critical angle when the real parts of the permittivity and permeability of the metamaterial are zero while the absolute imaginary parts can be arbitrarily small. The metamaterial layer needs a totally reflective substrate for perfect absorption, while this is not required for giant magnification.

Fig. 10 illustrates the investigated structure. A slab (zero index layer) is sandwiched between two semi-infinite layers, and the top layer, the slab, and the bottom layer are denoted as layers 0, 1 and 2, respectively.

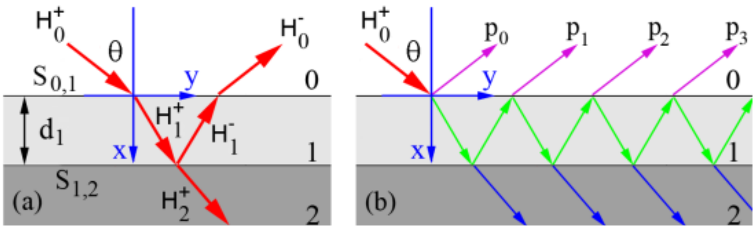

FIG. 10. Configuration for a slab of ZRM sandwiched between two semi-infinite layers. (b) Wave decomposition of the reflected or transmitted field.

Fig. 11 shows the reflectivity spectrum at different incident angles. At a critical incident angle, we can always get a minim reflectivity which almost equals to zero, no matter how small the thickness of slab becomes. This means that there exists an incident angle at which the incident plane wave is completely (100%) absorbed by the lossy slab.

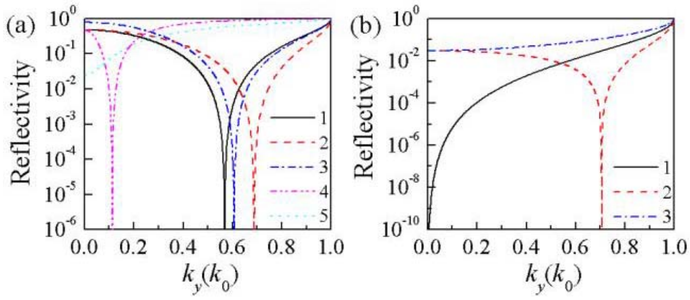

FIG. 11. Reflectivity of a slab with a PEC substrate.

4. Metamaterial absorbers can perfectly absorb an incident wave in a narrow frequency band. In this project, metamaterial absorbers are used to construct terahertz modulators by incorporating amorphous silicon in critical regions of metallic resonators. The conductivity of amorphous silicon will change with different pump power, consequently the absorption can be sensitively varied, and the reflected wave amplitude acting as the modulated signal can be strongly modulated. The schematic diagram of the modulator and some simulated results are shown in Fig. 12. The manuscript is in preparation.

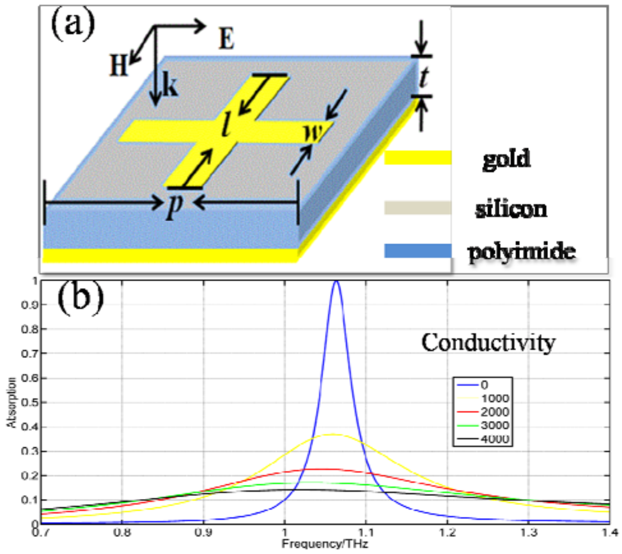

FIG. 12. (a) Schematic diagram of the modulator and (b) simulated results.

5. We have also achieved some other results under the support of current grant. For example, we have demonstrated an extremely sub-wavelength planar magnetic metamaterial made up of periodic dual layer spirals in the terahertz regime (see Fig. 13).

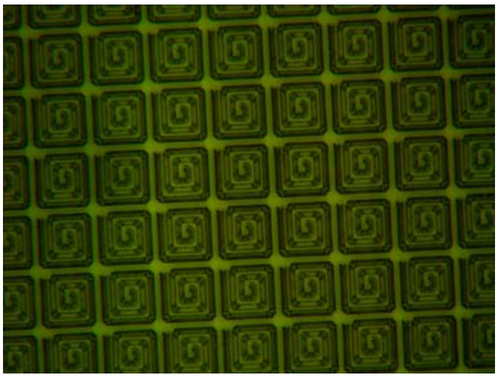

FIG. 13. Image of planar terahertz magnetic metamaterial.

Future works

We will experimental realize the EIT like phenomenon based on the planar metamaterial designed in this project and find its application as ultra-compact sensor with high sensitivity and figure of merit.

We want to utilize our broadband slow-wave absorbers in the application fields of photovoltaic devices, thermal emitters and high-responsivity broadband detector. We also want to extend their working frequency to terahertz frequency.

We will continue to exploit some abnormal properties and applications of zero-index artificial metamaterials.

We plan to study and fabricate RF/microwave/THz/optical metamaterials with artificial magnetic responses and explore their unique applications in some key technologies such as magnetic resonance imaging (MRI), ultrathin electromagnetic wave absorption, controlled THz radiation, and subwavelength imaging.

List of published journal papers that the present AOARD grant is acknowledged

1) Y. Cui, K. H. Fung, J. Xu, H. Ma, Y. Jin, S. He, and N. X. Fang, "Ultrabroadband Light Absorption by a Sawtooth Anisotropic Metamaterial Slab", Nano Lett., 12, 1443 (2012). (**Impact Factor: 12.219**)
2) Y. Cui, J. Xu, K. H. Fung, Y. Jin, A. Kumar, S. He, and N. X. Fang, "A thin film broadband absorber based on multi-sized nanoantennas", Appl. Phys. Lett., 99, 253101(2011).
3) D. Wang, J. Qian, S. He, J. Park, K. Lee, S. Han, Y. Mu "Aggregation-enhanced fluorescence in PEGylated phospholipid nanomicelles for in vivo imaging", Biomaterials, 32, 5880(2011). (**Impact Factor: 7.882**)
4) Y. Jin, S. Xiao, N. A. Mortensen, and S. He, "Arbitrarily thin metamaterial structure for perfect absorption and giant magnification", Opt. Express 19, 11114 (2011).

5) Y. He, H. Zhao, Y. Jin and S. He, “Plasmon Induced Transparency in Dielectric waveguide”, Appl. Phys. Lett. 99, 043113 (2011).

A few other papers are under review or in preparation.